RASTEP

A novel tool for nuclear accident diagnosis and source term prediction based on PSA and Bayesian Belief Networks

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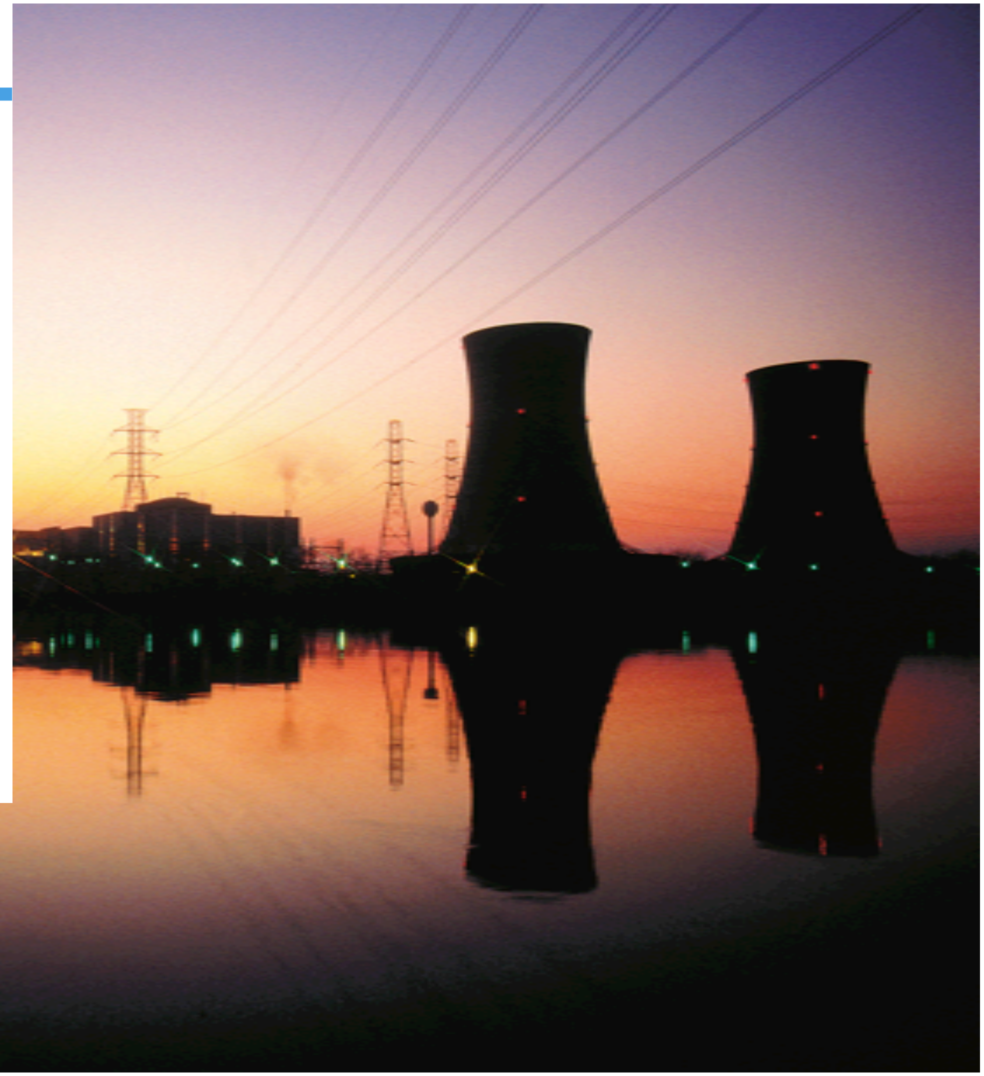
Lloyd's Register

RASTEP



Outline

- Introduction
- Aim and scope of the RASTEP project
- Introduction to Bayesian Belief Networks (BBN)
- Development of a BBN for a nuclear power plant
- Overview of the RASTEP tool
- The FASTNET project
- Conclusion

Introduction

- Early source term prediction in connection with severe accidents is crucial
  - Utilities predict source terms, and provide predictions to authorities
  - Nuclear safety authorities has often an important role after a severe accident, involving both communication and technical aspects
  - Authorities needs in-house source term prediction capability
- Plant PSA:s in many countries are detailed, full scope and continuously updated (yearly)
  - Increasingly used for risk informed applications
- Possibility to
  - Make use of the detailed PSA information for source term prediction
  - Make use of a BBNs' capabilities

Aim and scope of the RASTEP project

- The aim of the RASTEP project is to develop a tool for **RA**PID **S**OURCE **TE**RM **P**REDICTION for practical use in severe accident situations, considering the specific needs of SSM's emergency organization
- While RASTEP has been tailored to the needs of the Swedish Radiation Safety Authority (SSM) the tool as such is well-suited for the needs of any emergency response organization or nuclear operator
- The RASTEP project has been ongoing since 2009.
  - Including development of BWR and PWR models for Swedish NPPs
  - Part of the scope in current phase is to verify and compare RASTEP outputs with similar results from SSM's emergency preparedness organization
- RASTEP is one of the tools that are evaluated in the EU project FASTNET (FAST Nuclear Emergency Tools, www.fastnet-h2020.eu)
  - 2015 – 2019
  - 20 partners from 18 countries

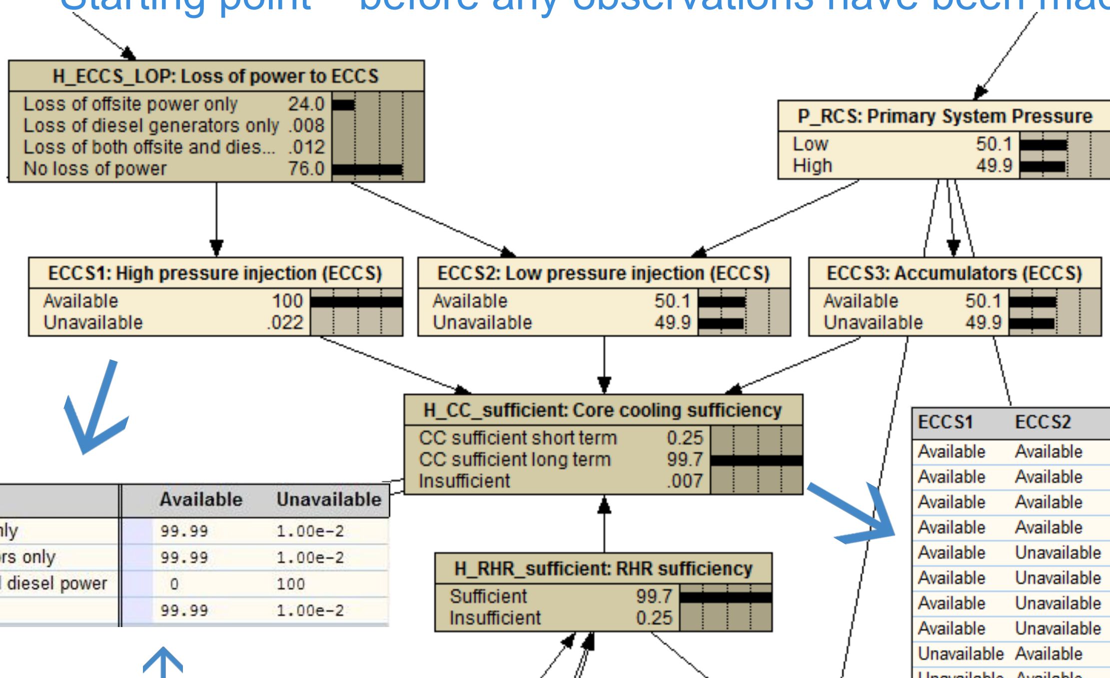
Introduction to Bayesian belief networks (BBN)

- In a BBN, one node is used for each variable, which may be discrete, continuous or propositional (true/false)
- Conditional probability is the basic concept in the BBN
- Using Bayes theorem, one's prior belief in the event (hypothesis) can be updated given the additional evidence (observation, finding)

$$P(State|Available\ information) = \frac{P(Available\ information|State) \cdot P(State)}{P(Available\ information)}$$

Example: BBN for emergency core cooling for PWR plant

Starting point – before any observations have been made



H_ECCS_LOP	Available	Unavailable
Loss of offsite power only	99.99	1.00e-2
Loss of diesel generators only	99.99	1.00e-2
Loss of both offsite and diesel power	0	100
No loss of power	99.99	1.00e-2

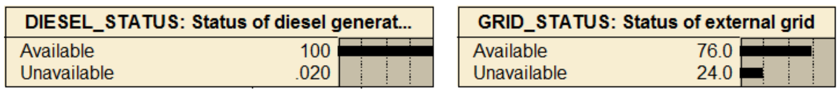
Conditional probability table (CPT) with statistical values

CPT with logical relations to other nodes

ECCS1	ECCS2	ECCS3	H_RHR_sufficient	Core cooling sufficiency
Available	Available	Available	Sufficient	CC sufficient long term
Available	Available	Available	Insufficient	CC sufficient short term
Available	Available	Unavailable	Sufficient	CC sufficient long term
Available	Available	Unavailable	Insufficient	CC sufficient short term
Available	Unavailable	Available	Sufficient	CC sufficient long term
Available	Unavailable	Available	Insufficient	CC sufficient short term
Available	Unavailable	Unavailable	Sufficient	CC sufficient long term
Available	Unavailable	Unavailable	Insufficient	CC sufficient short term
Unavailable	Available	Available	Sufficient	CC sufficient long term
Unavailable	Available	Available	Insufficient	CC sufficient short term
Unavailable	Available	Unavailable	Sufficient	CC sufficient long term
Unavailable	Available	Unavailable	Insufficient	CC sufficient short term
Unavailable	Unavailable	Available	Sufficient	CC sufficient long term
Unavailable	Unavailable	Available	Insufficient	CC sufficient short term
Unavailable	Unavailable	Unavailable	Sufficient	Insufficient
Unavailable	Unavailable	Unavailable	Insufficient	Insufficient

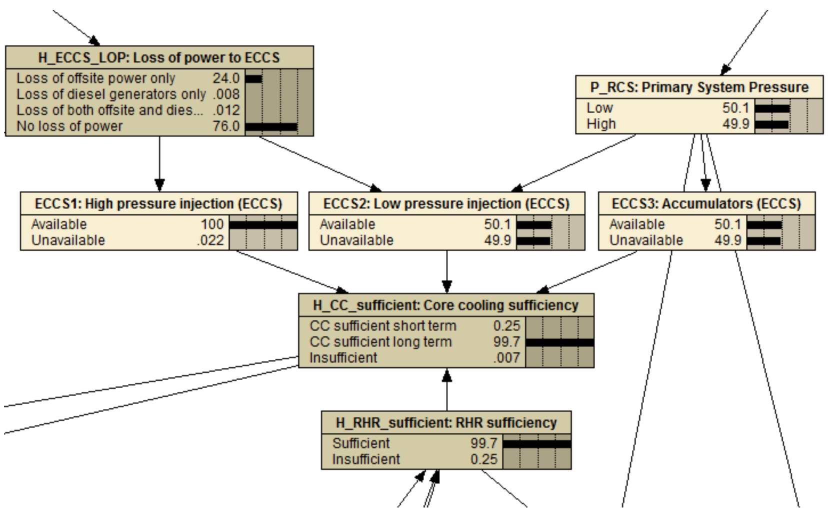
Example: BBN for emergency core cooling for PWR plant

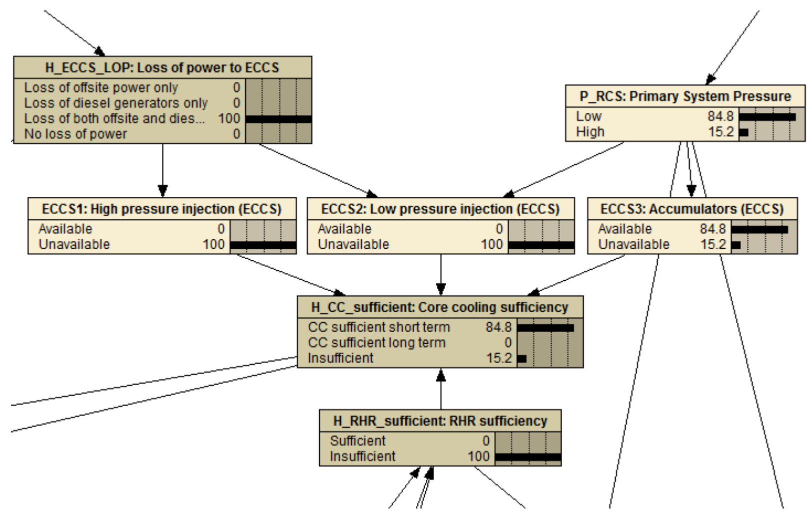
Starting point (as in previous slide)



Updated beliefs due to observations

Leads to update of belief in all nodes



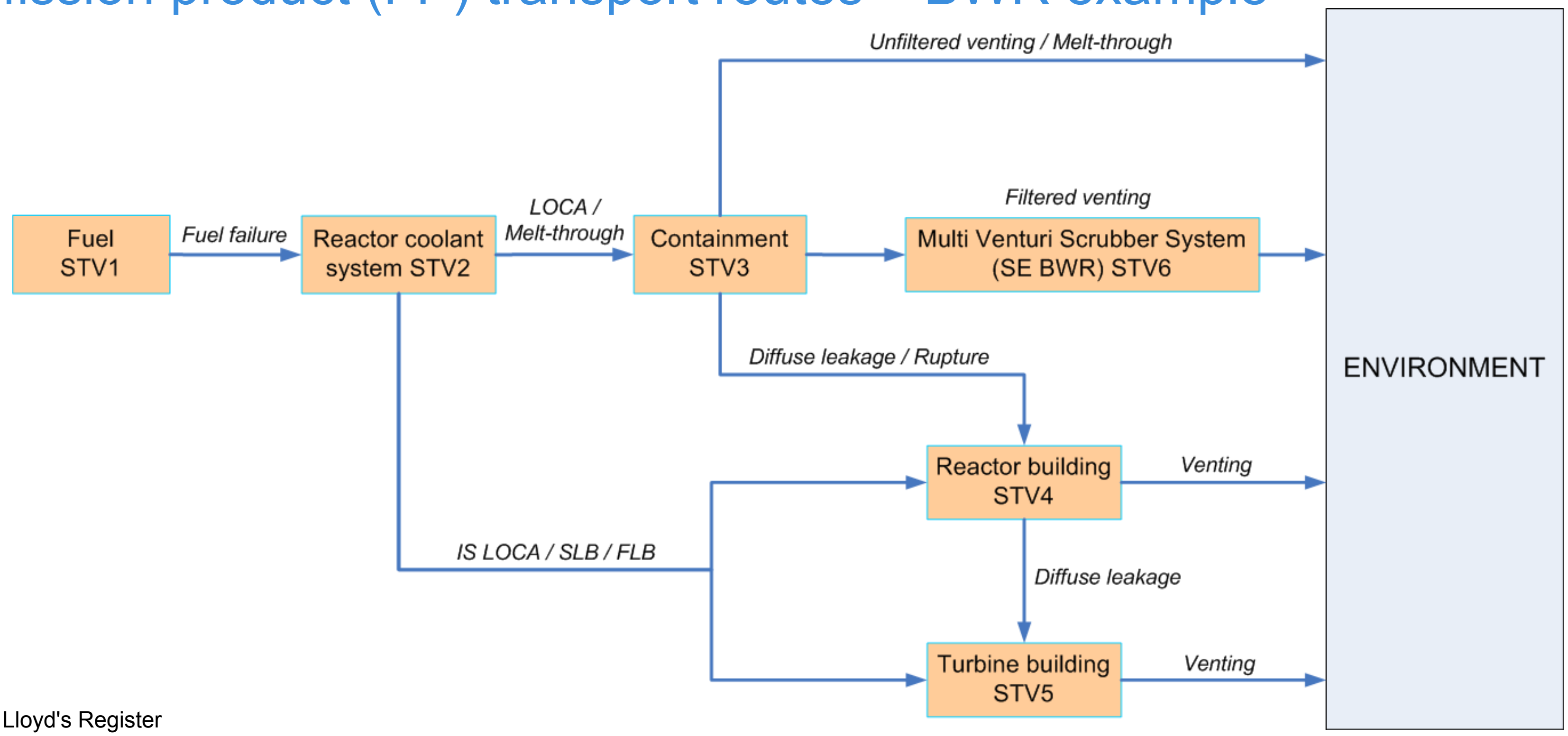


Developing a BBN for an NPP

- Mapping of plant characteristics
  - Definition of the physical source term volumes (STV) to be considered
  - Fission product (FP) transport and release routes
  - Mapping of severe accident management systems and actions
  - Key plant systems
  - Observable plant state parameters
  - Physical phenomena
- Development of the model
  - Model structure
  - Conditional Probability Tables (CPTs)

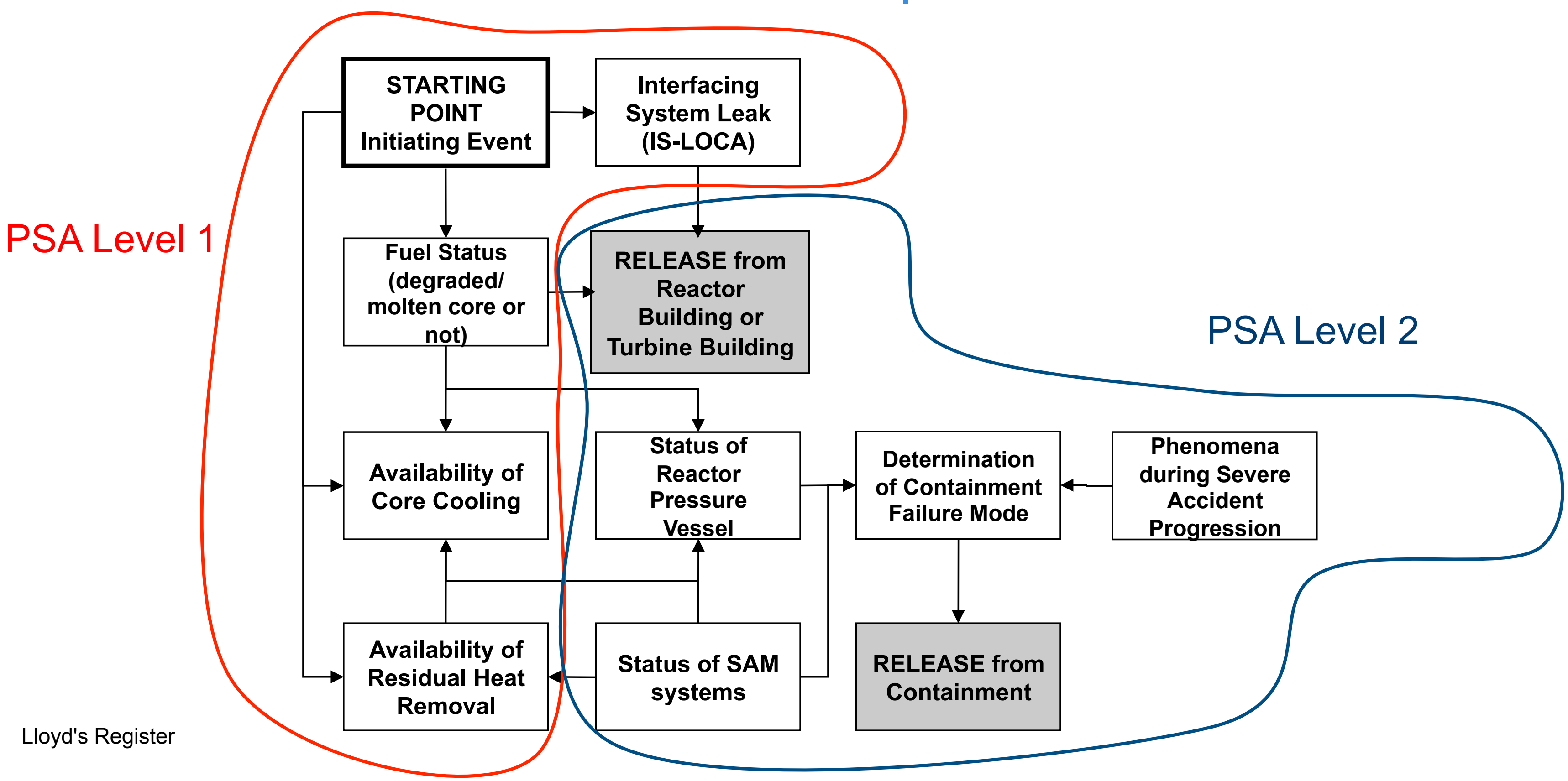
Mapping of plant characteristics

Release path diagram showing source term volume (STV) and fission product (FP) transport routes – BWR example

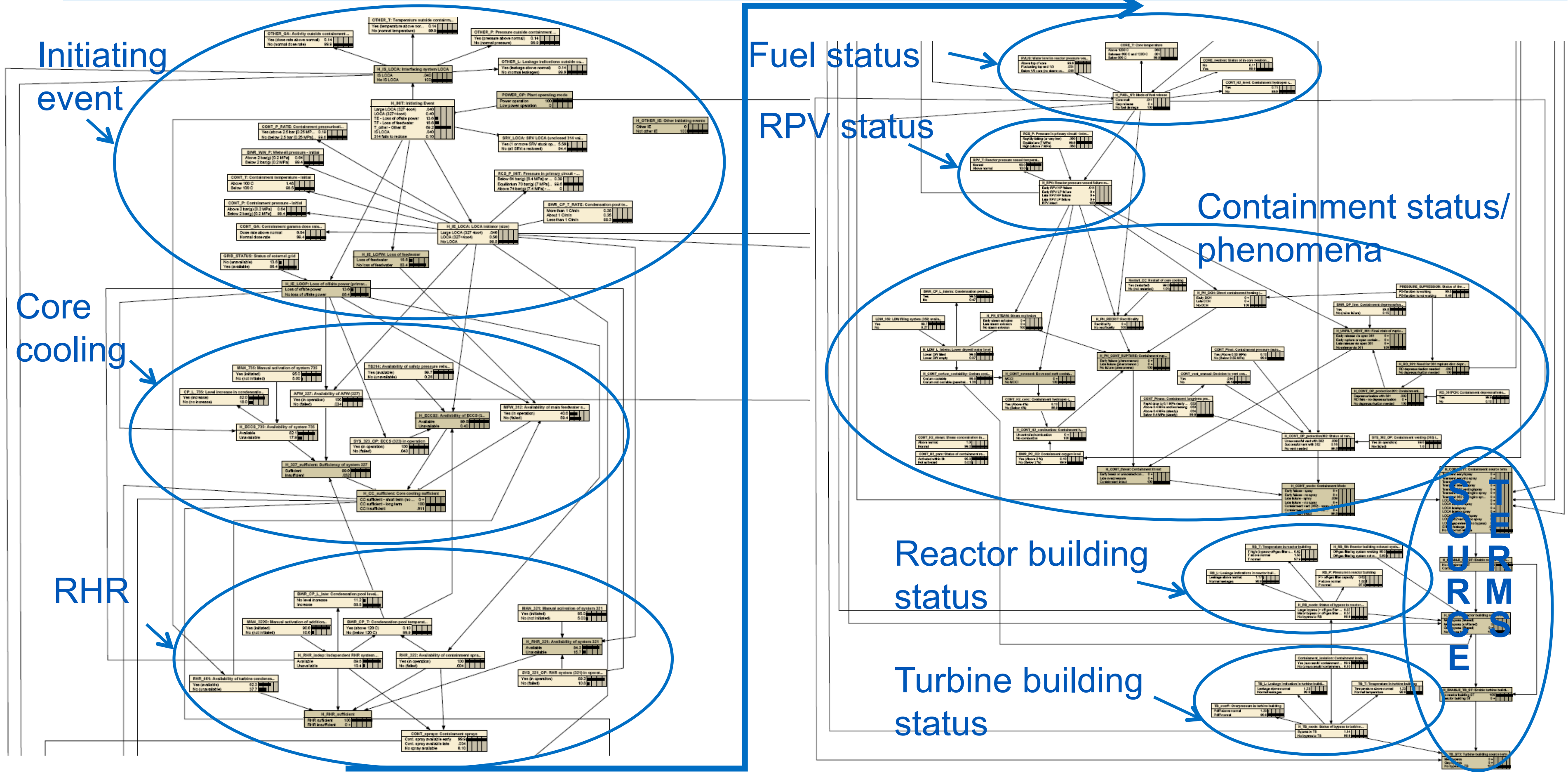


Development of the model

General model structure – BWR example



Subnetworks – example – BBN of a Swedish BWR



Conditional Probability Tables – node categories

Node category	Determination of CPTs
Boundary condition node	Either 1 or 0, determined by user
Initiating event node	Derived from the **initiating events (IE)** in the **PSA model**
System or function performance node	Derived from **basic events or fault tree analysis cases in the PSA model**
Outcome determining node / source term node	Complex relationships, may rely on a mixture of engineering judgement, general considerations and calculations with the PSA, e.g. phenomena probabilities.
Measurement node	Consider both loss of detection and spurious detection. Prior assumptions regarding these failure modes are based on measurement component **unavailability data**.

PSA data – CPT modelling – BWR example

Prior probabilities are modelled using PSA data for:

- Initiating events

H_INIT: Initiating Event	
Large bottom LOCA	0.12
Large top LOCA	.050
Small bottom LOCA	0.38
Small top LOCA	0.01
TE - Loss of offsite power	14.7
SBO	0.01
TF - Loss of feedwater	1.59
LUHS	.020
T_other - Other IE	83.0
IS/V LOCA	.040
SRV fails to reclose	0.10

SRV_LOCA: SRV LOCA (SRV stuck open)	
Yes (1 or more SRV stuck op...	1.85
No (all SRV:s reclosed)	98.2

- Systems

H_ECCS2: Availability of ECCS	
Available	1.32
Unavailable	98.7

- System function, requirements

H_IE_LOCA: LOCA initiator (size)	
Large bottom LOCA	0.12
Small bottom LOCA	0.38
Large top LOCA	.050
Small top LOCA	0.11
No LOCA	99.3

CC_AFW: Status of auxiliary feedwater sys...	
Available	97.8
Unavailable	2.24

- Manual actions

RHR_RHRSYS_MAN: Activation of residual ...	
Yes (activated)	97.0
No (not activated)	3.00

MAN_SPRAY_INDEP: Activation of indepen...	
Yes (activated)	97.0
No (not activated)	3.00

- Phenomena

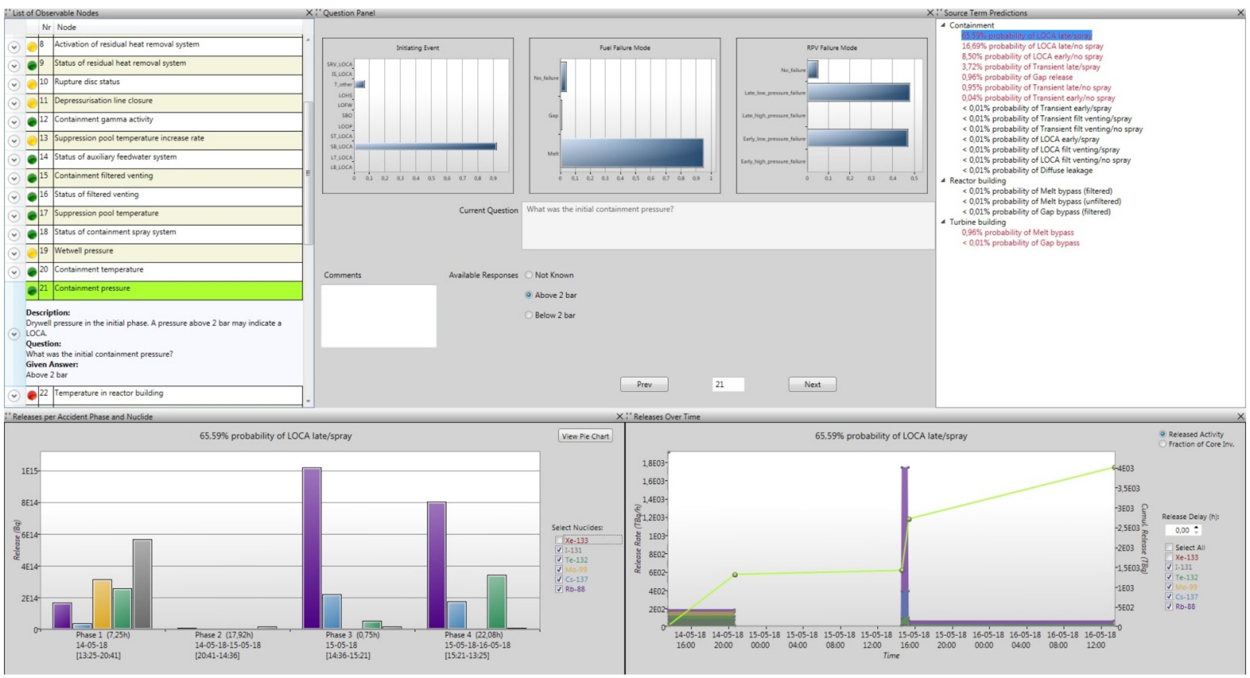
H_PH_DCH: Direct containment heating (D...	
Early DCH	0 +
Late DCH	0 +
No DCH	100

H_PH_CONT_RUPTURE: Containment rupt...	
Early failure (phenomenon)	0.31
Late failure (phenomenon)	0.32
No failure (phenomena)	99.4

Graphical user interface

Question panel
- Visualization of the prediction for status of the initiating events, fuel and reactor vessel.
- Questions with possible answers to choose from.
- Opportunity to enter comments for specific issues / nodes.

List of observable nodes/questions
- Numbered questions linked to the relevant node in the BBN.
- Possibility to jump between questions.
- Detailed description for each node.

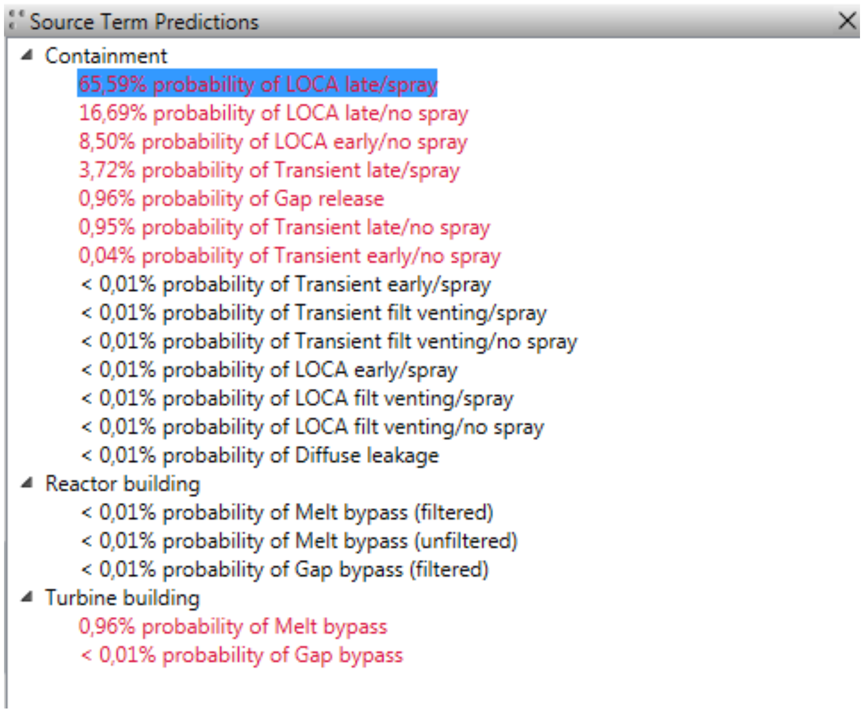


Source term prediction
- List of available source terms with related probabilities.
- The selected source term is shown in the graphs below.

Activity per phase
- Visualization of activity for individual nuclide groups per phase (histograms).
- Possibility to view the distribution of nuclides per phase with pie charts.

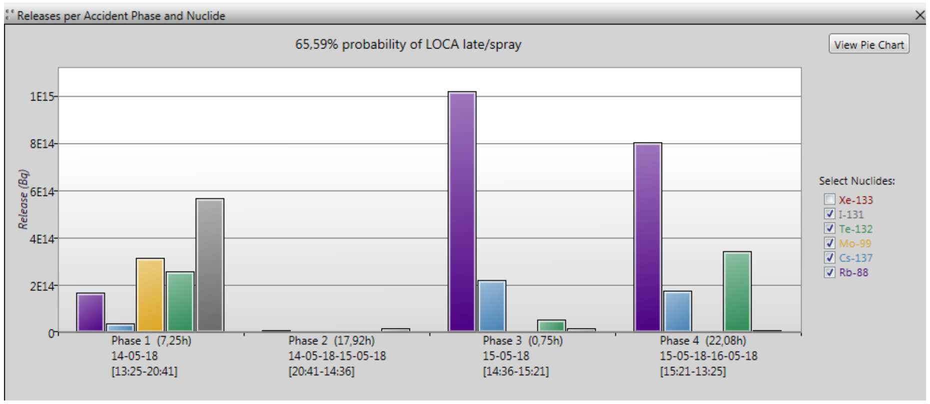
Releases over time
- Diagram showing emission for individual nuclide groups and total emissions (activity) over time.
- Possibility to show fractions of core inventory.

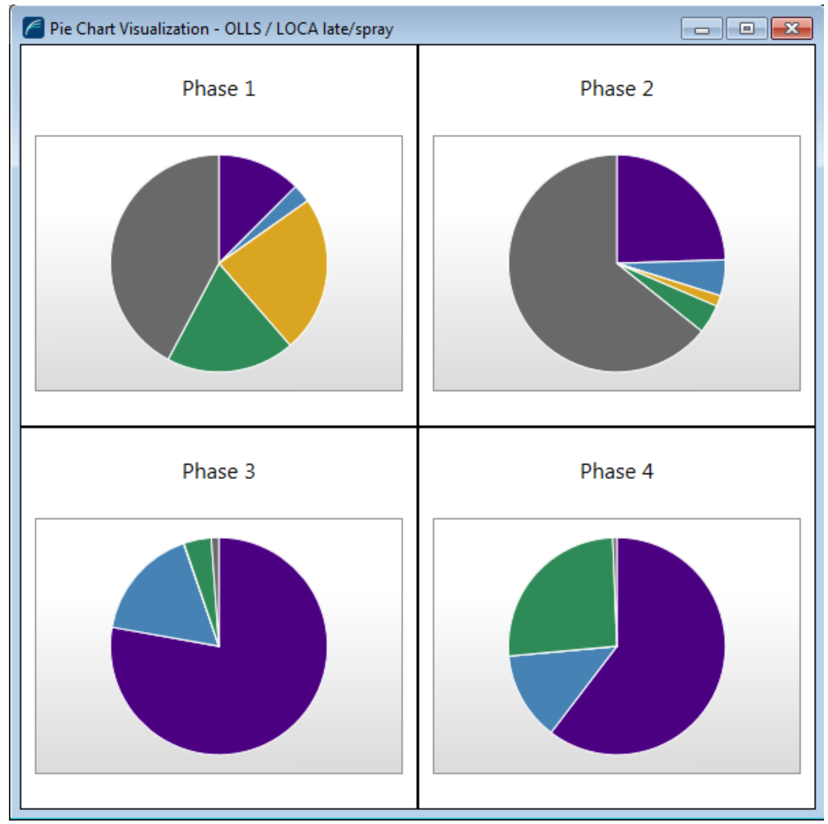
Source term prediction



- While responding to questions the source term prediction updates.
- The most probable sequence/source term is shown with a given probability on top of the list.
- Three possible locations for release (BWR model example):
  - Containment
  - Reactor building
  - Turbine building

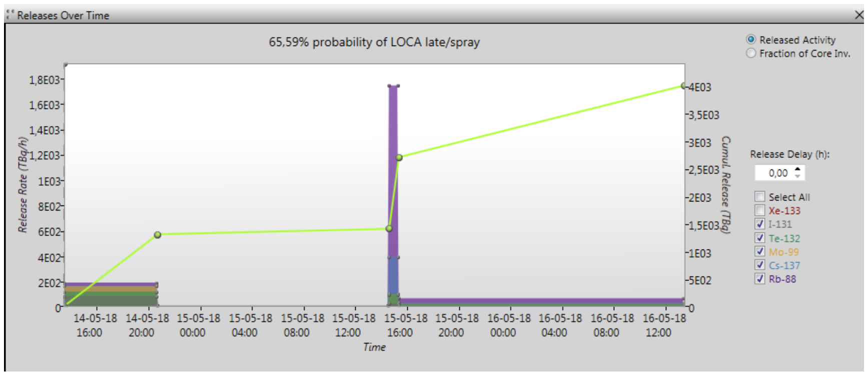
Source term visualization per phase

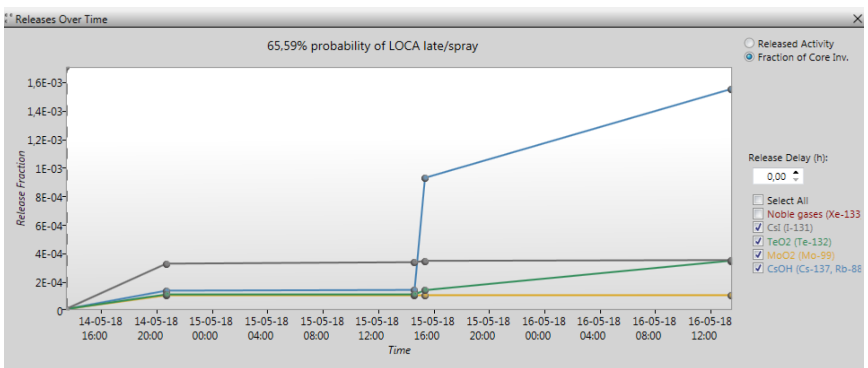




- Histograms show source term per phase
- Pie-chart graphs show:
  - Release distribution per nuclide group per phase
  - Activities per nuclide group per phase

Source term visualization





- Activity release rates as histogram (TBq/h).
- Interpolation between points for time phases providing a rough estimation of cumulative released activity (TBq).
- Six nuclides that can be chosen separately.
- Fractions of core inventory in match with MAAP/MELCOR results.

RASTEP Case Report

RASTEP

RASTEP Case Report

RASTEP Model: *RASTEP Project*

Reactor trip date and time: *14-05-2018 01:25:53*

Date and time of generation of the report: *14-05-2018 02:30:32*

65,59% probability of LOCA late/spray

Pre-calculated source term: OLLS Late containment overpressure, initiating event LOCA and successful containment spray system.

Sequence: The analysis presents the course of events following the containment overpressure due to failed containment spray and unsuccessful opening of filtered venting. The water pumping is stopped when 11 m water are reached in the drywell and a signal of containment failure is "triggered". The reactor trip, forced blowdown and closing of isolation valves succeed. All coolant make-up fails initially and no "recovery" of coolant make-up is available even after incipient core damage. The containment is inert and no hydrogen combustion occurs. Nor occurs physical phenomena that threaten the integrity of the containment but the reactor pressure vessel failure occurs. Flooding of the lower drywell works.

Figure 1: Activity Release per Phase [Bq]

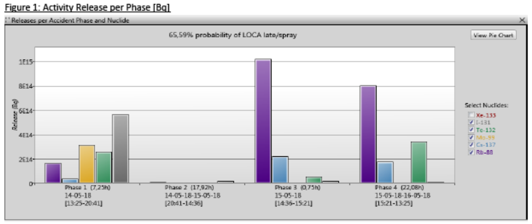


Table 1: Activity Release per Phase [Bq]

	Phase 1 (7,25h) 14-05-18 [13:25-20:41]	*Phase 2 (17,92h) 14-05-18-15-05-18 [20:41-14:36]*	*Phase 3 (0,75h) 15-05-18 [14:36-15:21]*	*Phase 4 (22,08h) 15-05-18-16-05-18 [15:21-13:25]*
Xe-133	1,054E+16	6,574E+16	2,573E+18	6,393E+16
I-131	5,636E+14	1,675E+13	1,481E+13	8,065E+12
Te-132	2,556E+14	1,121E+12	5,364E+13	3,417E+14
Mo-99	3,118E+14	4,275E+11	1,061E+12	9,784E+09
Cs-137	3,643E+13	1,395E+12	2,215E+14	1,748E+14
Rb-88	1,672E+14	6,397E+12	1,015E+15	8,004E+14

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Figure 2: Activity Release Rate [TBq/h] and Cumulative Release [TBq] over time

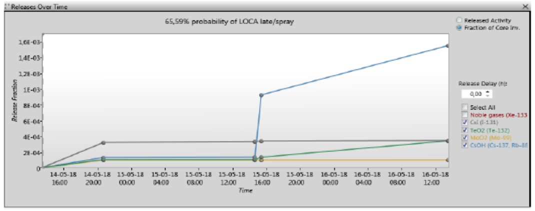

Table 2: Cumulative Activity Release [Bq]

	Phase 1 (7,25h) 14-05-18 [13:25-20:41]	*Phase 2 (17,92h) 14-05-18-15-05-18 [20:41-14:36]*	*Phase 3 (0,75h) 15-05-18 [14:36-15:21]*	*Phase 4 (22,08h) 15-05-18-16-05-18 [15:21-13:25]*
Xe-133	1,054E+16	7,628E+16	2,65E+18	2,713E+18
I-131	5,636E+14	5,804E+14	5,952E+14	6,032E+14
Te-132	2,556E+14	2,567E+14	3,103E+14	6,521E+14
Mo-99	3,118E+14	3,122E+14	3,132E+14	3,133E+14
Cs-137	3,643E+13	3,783E+13	2,594E+14	4,342E+14
Rb-88	1,672E+14	1,736E+14	1,189E+15	1,989E+15

Table 3: Fractions of Core Inventory [-]

	Phase 1 (7,25h) 14-05-18 [13:25-20:41]	*Phase 2 (17,92h) 14-05-18-15-05-18 [20:41-14:36]*	*Phase 3 (0,75h) 15-05-18 [14:36-15:21]*	*Phase 4 (22,08h) 15-05-18-16-05-18 [15:21-13:25]*
Noble gases (Xe-133)	3,011E-03	2,353E-02	9,118E-01	9,353E-01
CsI (I-131)	3,19E-04	3,29E-04	3,385E-04	3,439E-04
TeO2 (Te-132)	1,031E-04	1,036E-04	1,329E-04	3,391E-04
MoO2 (Mo-99)	9,665E-05	9,681E-05	9,728E-05	9,728E-05
CsOH (Cs-137, Rb-88)	1,296E-04	1,346E-04	9,231E-04	1,545E-03

The FASTNET project

Objectives

- Set-up severe accident scenarios databases
- Qualify a common response methodology that integrates tools and methods to:
- Evaluate the source term
- Ensure diagnosis and prognosis of accident progression
- Make connection between FASTNET tools and other systems that use source term definition for further assessments
- Propose communication to the public of emergency management approaches, measures and resources in Europe

Work packages

- WP1 – Scenarios database
- WP2 – Emergency preparedness
  (incl. evaluation of BBN techniques)
- WP3 – Emergency response
  (incl. BBN approaches)
- WP4 – Emergency exercises
- WP5 – Dissemination
  (knowledge sharing and training)
- WP6 – Project management

Conclusions

- RASTEP provides emergency preparedness organisations with an independent view of an accident progression and possible off-site consequences
- RASTEP makes it possible for utilities to quickly take relevant accident mitigating actions following a nuclear power plant accident
- RASTEP provides authorities with information following a nuclear power plant accident for prioritisation of actions and/or giving recommendations to emergency response organisations

Thank you

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